REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-01-

0607

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searcl ~~ewing~~
the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including sugges ~~nation~~
Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperw

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		01 JAN 99 - 30 NOV 01

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Experimental Investigation of Upper Atmospheric Turbulence Models	F49620-99-1-0088

6. AUTHOR(S)

Dr. Michael Roggemann

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Professor of Electrical Engineering Department of Electrical Engineering Michigan Technological University 1400 Townsend Drive Houghton, MI 49931	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFOSR/NM 801 N. Randolph Street Room 732 Arlington, VA 22203-1977	F49620-99-1-0088

11. SUPPLEMENTARY NOTES

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
NOTICE OF TRANSMITTAL DTIC. THIS TECHNICAL REP(
HAS BEEN REVIEWED AND IS APPROVED FOR PUBLIC F
LAW AFR 190-12. DISTRIBUTION IS UNLIMITED.

12a. DISTRIBUTION AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Theoretical investigation of estimating turbulence statistical parameters from balloon-borne anemometer array measurements. The goal of this task is to develop the theoretical and computer modeling tools needed to investigate the turbulence strength, the isotropic nature of the turbulence, and the spatial correlation properties of the turbulence, or equivalently the spatial power spectral density, of the index of refraction fluctuations in the upper atmosphere using ha] loon borne anemoneter measurements as the input. Balloon borne experiment design, construction, and test. In this task we are designing, constructing, and testing a balloon-borne anemometer system which will measure atmospheric turbulence based on temperature data, allowing the theoretical investigations described in Task I to be tested with experimental data. Experimental campaigns and data reduction: The goal of this task is to conduct a very limited number of data collection campaigns at a variety of locations and times of day The purpose of these tests is not to establish a world wide data base, hut rather to demonstrate that there are quantifiable differences between data collected without any assumptions, and the present data.

20011212 095

14. SUBJECT TERMS	15. NUMBER OF PAGES
	6
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

Final

Experimental Investigation of Upper Atmospheric Turbulence Models

Michael C. Roggemann, Ph.D.
Professor of Electrical Engineering
Department of Electrical Engineering
Michigan Technological University
1400 Townsend Drive
Houghton, MI 49931

phone: (906) 487-2164
fax: (906) 487-2949
e-mail: mroggema@mtu.edu

Objectives

1. Theoretical investigation of estimating turbulence statistical parameters from balloon-borne anemometer array measurements.

> The goal of this task is to develop the theoretical and computer modeling tools needed to investigate the turbulence strength, the isotropic nature of the turbulence, and the spatial correlation properties of the turbulence, or equivalently the spatial power spectral density, of the index of refraction fluctuations in the upper atmosphere using balloon borne anemometer measurements as the input.

2. Balloon borne experiment design, construction, and test.

> In this task we are designing, constructing, and testing a balloon-borne anemometer system which will measure atmospheric turbulence based on temperature data, allowing the theoretical investigations described in Task 1 to be tested with experimental data.

3. Experimental campaigns and data reduction.

> The goal of this task is to conduct a very limited number of data collection campaigns at a variety of locations and times of day. The purpose of these tests is not to establish a world wide data base, but rather to demonstrate that there are quantifiable differences between data collected without any assumptions, and the present data.

Status of Effort

Turbulence induced index of refraction fluctuations affect the performance of laser beam propagation systems used in the atmosphere. Propagating a laser beam through a turbulent medium results in decorrelation of the wave front, broadening of the target spot size and possibly shifting the centroid of the beam. Turbulent effects occur at all altitudes and are stronger in the lower atmosphere. At higher altitudes, turbulent effects can be strong if it is necessary to propagate the laser beam over a significantly long path. For example, in the case of the Airborne Laser (ABL) system it is necessary to propagate a laser beam over a path on the order of several tens to a few hundred kilometers at altitudes exceeding 10 kilometers. These path lengths are significant enough to strongly influence the ability to aim and focus the beam on a moving target. The models for the optical effects of turbulence in the lower atmosphere are well understood, and most experiments agree with predictions.

There is a significant body of experimental evidence from measurements of turbulence made at high altitudes which conflict with the assumptions of isotropy and homogeneity. Anisotropy of turbulence has been demonstrated in laboratory investigations, even at Reynolds numbers well beyond the critical Reynolds numbers for the flow geometry. Since the tropopause is known to have fluid flow properties similar to the shear layers created in laboratory, these studies cast doubt on the correctness of the conventional assumption of isotropic turbulence through the entire atmosphere. Measurements taken near the ground have also shown anisotropic behavior of the turbulence. Dalaudier, et al. have collected data at high altitudes that indicate the existence of anisotropic turbulence and non-Kolmogorov behavior. Finally, nearly all of the non-flight test data taken to date has been collected from sensors towed behind a rising balloon. However, wake turbulence arising from the blunt body of the balloon may corrupt these measurements, providing motivation for the experiment resulting in the data presented here.

Methods for data reduction and parameter estimation have been developed under this effort to process data from an experiment that made temperature measurements from altitudes of 12,000 to 18,000 meters. The experiment was designed to make temperature measurements with 13 anemometers or probes placed on the perimeter of a hexagonal grid, with 2 additional anemometers placed at the ends of two arms extending from a hexagonal array. During the experiment, technical difficulties beyond our control prevented us from collecting data from 8 of the probes.

Both parameter estimation approaches developed use sample-based estimates of the spatial autocorrelation of the index of refraction fluctuations for separations corresponding to all possible pairs of probes by averaging data taken over 3 to 6 meter slabs of the atmosphere. In the estimation approaches applied so far, the index of refraction fluctuations are explicitly assumed to be homogeneous and isotropic. This assumption is enforced in the parameter estimation by treating the vector separations of the probes as scalars. The spatial autocorrelation estimates are used in two maximum likelihood-based nonlinear optimization routines to estimate the turbulence parameters of interest. For the von Karman spectrum, there are three parameters of interest: the outer

scale L_0; the inner scale l_0; and a constant which describes the strength of the fluctuations denoted by C_n^2 and referred to as the structure constant of the turbulence. As noted in our previous studies, this technique is not able to accurately estimate l_0 due to poor sampling at small spatial separations, and the requirement for extremely high signal-to-noise ratios. Hence, no effort to estimate l_0 was made here. We have implemented a von Karman-like model for the spatial power spectrum of the index of refraction fluctuations which allows the exponent on the wavenumber in the denominator to vary from the value of 11/6 derived for the von Karman model and eliminates the exponential term containing the inner scale. In the model developed later, we denote the denominator exponent by the symbol α. When $\alpha \neq 11/6$ the constant in the numerator cannot be denoted by C_n^2 since this constant would have different units and could not be inserted into equations derived from the von Karman model, thus we introduce the symbol P_C to represent the proportionality constant.

Accomplishments/New Findings

The balloon flight took place during the early morning of August 20, 2000 over the White Sands Missile Range. The flight was conducted by the Air Force Research Laboratory balloon launch facility at the Nenninger Site on Holloman AFB, New Mexico. Due to the sensitive nature of the probes, the entire flight was conducted at night with no cloud cover. To successfully carry the estimated 700 kilogram payload, a 17,640 cubic meter, 1.5 millimeter thick, helium filled balloon was used, manufactured by Winzen. The original flight plan called for the balloon to ascend to approximately 21 kilometers and release helium to begin a controlled descent at a rate of 4 m/s to an altitude of 10 kilometers. At that point, ballast was to be dropped so that the balloon would rise, and the flight profile repeated. Due to the failure of the ballast release mechanism, only one controlled descent was possible, lasting approximately 150 minutes. During the flight, the tropopause began at approximately 15,500 meters and extended above the apex of our flight profile. After the flight profile was completed, the balloon was released and the payload returned to earth via a parachute.

During the balloon's descent, temperature measurements were made using 3.8 micron diameter, 1.27 millimeter long, TSI model 1210-T1.5 thin wire anemometers. The anemometers were operated in a constant current, low over heat mode making them sensitive to temperature fluctuations. To improve sensitivity to small temperature fluctuations, the output of the probes was filtered into a low frequency component and a high frequency component. This was done because the low frequency component arising from the nominal macroscopic temperature would saturate the analog to digital converter designed for milliKelvin resolution. The low frequency component was filtered with cutoffs between DC and 1 Hz, while the high frequency component was filtered with cutoffs between 0.5 Hz and 200 Hz. The high frequency component of each probe was sampled at 1562 samples/second with 16 bits of resolution. The low frequency component of each probe was sampled at 156 samples/second also with 16 bits of resolution. In addition to the high resolution temperature sensing package, the balloon

was instrumented with a three axis attitude sensing package, a pressure sensor, a global positioning system, and an ambient temperature sensor. The attitude sensing package allows the temperature measurements to be registered in three dimensional space if the balloon is swinging or rotating. The pressure sensor was required because the atmospheric pressure varied significantly over the balloon flight, and index of refraction fluctuations are function of both temperature and pressure. All of the high resolution temperature data and the auxiliary data was transmitted to the ground in real time and recorded on magnetic tape drives.

In conjunction with the measurements made in descent, standard thermosonde turbulence measurement packages provided and flown by the Geophysics Directorate were carried aloft on weather balloons in the standard manner for making turbulence profile measurements. We are grateful for their interest and support of this effort.

Comparison of the results obtained with the descending turbulence array and the standard thermosonde package show reasonable agreement for C_n^2 when $\alpha = 11/6$ is forced in the data processing for the descending turbulence array data, and in this case the outer scales calculated are on the order of a few to several tens of meters. However, smaller errors between the measured data and the curves created by the parameter fitting approach were obtained when all three parameters were estimated, indicating that the turbulence at these altitudes may not behave according to the Kolmogorov or von Karman models. In this case, the smallest errors resulted when $\alpha < 11/6$, and outer scales were in the few to several meters range. These results indicate that further studies should be made of high altitude turbulence to more fully understand the nature of the turbulence at those altitudes, allowing the optical effects arising from this turbulence to be better modeled.

Personnel Supported

Michael C. Roggemann, Professor of Electrical Engineering
Two EE Graduate Students

Publications

M. C. Roggemann, and W. R. Reynolds, "A block matching algorithm for mitigating aliasing effects in undersampled image sequences", accepted for publication in *Opt. Eng.*, October, 2001.

J. B. Burl, M. C. Roggemann, and B. M. Welsh, "Tilt estimation in moderate to strong scintillation", *Appl. Opt.*,, vol. 40, p2966-2972, 2001.

B. L. Evans, J. B. Martin, L. W. Burggraf, and M. C. Roggemann, "Demonstration of energy-coded Compton scatter tomography with fan beams for one-sided inspection", accepted for publication in *Nuclear Instruments and Methods*, March 2001.

W. W. Brown, M. C. Roggemann, T. J. Schulz, T. C. Havens, J. T. Beyer, and L. J. Otten, "A measurement and data processing approach for estimating the spatial statistics

of turbulence-induced index of refraction fluctuations in the upper atmosphere", *Applied Optics*, vol 40, p1863-1871, 2001.

L. J. Otten, A. Jones, D. Black, J. Lane, R. Hugo, M. C. Roggemann, and J. T. Beyer, "Precision Tropopause Turbulence Measurements", Proc. SPIE on Propagation and Imaging through the Atmosphere, vol. 4125 ,M. C. Roggemann, ed., p33-40, 2000.

M. C. Roggemann, "Adaptive Optics - Past, Present, and Future", invited paper presented at the Annual Meeting of the Optical Society of America, Providence, Rhode Island, October, 2000.

M. C. Roggemann, B. M. Welsh, and T. L. Klein, "Algorithm to reduce anisoplanatism effects on infrared images", *Proceedings of the SPIE on Wave Propagation and Imaging Through the Atmosphere IV*, vol. 4125, p140-149, July 2000.

Interactions/Transitions

We have coordinated closely with the Airborne Laser (ABL) Technology Branch at Kirtland AFB, NM, to maximize the impact of this experiment for the ABL system. We are also working closely with AFRL Geophysics Directorate scientists to share data and maximize the scientific impact of the experiment.

New discoveries, inventions, or patent disclosures

No inventions or patent disclosures have resulted from this work.

Honors/Awards

Dr. Roggemann was elected a Fellow of the Optical Society of America in 2000. He chaired the SPIE Kingslake Medal committee in 2000 choose the most outstanding paper published in an SPIE journal, and will serve again in this capacity in 2001. Prof. Roggemann is also the topical editor of the *Journal of the Optical Society of America A* for atmospheric optics.

Additional Data

Top Research Achievement

Our top research accomplishments this year have been the successful execution of the balloon experiment and the reduction of the data, along with the comparisons to the conventional weather balloon measurements made by the Geophysics directorate. The indications that turbulence in the tropopause may not obey Kolmogorov statistics may impact the ABL adaptive optical system design and performance modeling.

Technology Transition or Transfer

We are presently preparing our findings for submission to a refereed archival journal. We are collaborating with researchers and the Geophysics Directorate, and will likely jointly author our findings.